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## Thermal Dimuon Emission in In-In at the CERN SPS

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(NA60 Collaboration)

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The NA60 experiment at the CERN SPS has studied low-mass dimuon production in 158A GeV In-In collisions. A significant excess of pairs is observed above the yield expected from neutral meson decays, consistent with a dominant contribution from  $\pi\pi \rightarrow \rho \rightarrow \mu\mu$ . This paper presents precision results on the mass and transverse momentum spectra of the excess pairs. The space-time averaged rho spectral function associated to the measured mass distribution shows a significant broadening, but essentially no mass shift. The slope parameter  $T_{eff}$  extracted from the spectra rises with dimuon mass up to the  $\rho$ , followed by a sudden decline above. While the initial rise is consistent with the expectations for radial flow of a hadronic decay source, the decline indicates a transition to an emission source with much smaller flow, possibly of partonic origin.

The ultimate goal of heavy ion collisions is the detection of signatures of a phase transition from hadronic matter to a deconfined and/or chirally restored medium. Lepton pairs are a powerful probe of the hot and dense fireball formed in high-energy nuclear collisions. They are produced during the entire space-time evolution of the fireball and freely escape, undisturbed by final state interactions. In the invariant mass region  $<1$  GeV, thermal dilepton production is mediated by the broad vector meson  $\rho(770)$ . In the mass region  $>1$  GeV, thermal dileptons may be produced in either the early partonic or the late hadronic phase of the fireball.

In contrast to real photons, virtual photons decaying into lepton pairs can be characterized by two variables, mass  $M$  and transverse momentum  $p_T$ . The mass distribution can be directly connected to the space-time averaged spectral function of the intermediate vector meson. The measurement of  $p_T$  spectra of lepton pairs may offer access to their emission region, as  $p_T$  encodes the key properties of the expanding fireball (temperature and transverse flow). While hadrons always receive the full asymptotic flow reached at the moment of decoupling from the

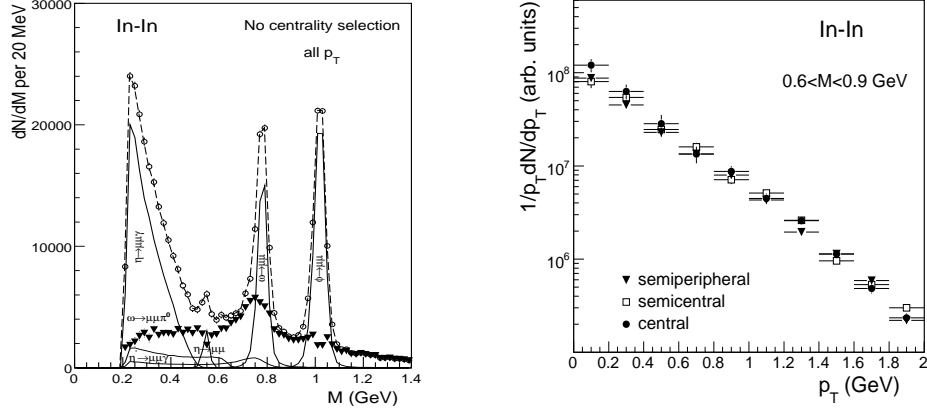


Figure 1: Left: Isolation of an excess above the electromagnetic decays of neutral mesons (see text). Total data (open circles), individual cocktail sources (solid), difference data (thick triangles), sum of cocktail sources and difference data (dashed). Open charm not subtracted. Right: Transverse momentum spectra of the rho-like mass region for three centrality windows, arbitrarily normalized. The errors are purely statistical

flowing medium<sup>5,6</sup>, lepton pairs are continuously emitted during the evolution of the system. They are thus produced with small flow and high temperature at early times, and larger flow and smaller temperatures at later times.

The NA60 experiment measured low-mass dimuon production in 158A GeV In-In collisions. The centrality-integrated net mass spectrum after subtraction of backgrounds<sup>14</sup> is shown in Fig. 1. It contains about 430 000 dimuons in the mass range  $\leq 1.4$  GeV. The mass resolution at the  $\omega$  is 20 MeV. The data are divided in centrality bins using the measured charged track density. While peripheral data can be described as a superposition of expected contribution from the electromagnetic decays of neutral mesons (“hadron cocktail”), this is not possible for the total data, due to the existence of a strong excess of pairs. To isolate this excess without any fits, the decay sources are subtracted from the data using local criteria which are only based on the measured mass distribution. The procedure is illustrated in Fig. 1. The narrow  $\omega$  and  $\phi$  peaks are fixed in order to get a smooth underlying continuum after subtraction. The yield of the  $\eta$  relative to the  $\omega$  and  $\phi$  is fixed from the data at  $p_T > 1.0$  GeV. This contribution is relevant only for masses  $\leq 0.4$  GeV. The  $\eta$  two-body and  $\omega$  Dalitz decays are then fixed as well. The ratio  $\eta'/\eta$  is assumed to be 0.12<sup>15</sup>. The  $\rho$  is not subtracted. Open charm, measured to be  $0.30 \pm 0.06$  of the total yield in the mass interval  $1.2 < M < 1.4$  GeV<sup>16</sup>, is subtracted throughout (but not yet in Fig. 1), with the spectral shape in  $M$  and  $p_T$  as described by Pythia<sup>16</sup>. For a detailed discussion of the subtraction procedure and associated systematic uncertainties see Ref. <sup>20,21</sup>. After subtraction of the meson decays and charm, the remaining sample contains  $\sim 150$  000 dimuons. The subtracted data for the  $\eta$ ,  $\omega$  and  $\phi$  provide the  $p_T$  spectra for these mesons and are used later for comparison. A strong excess is found, with respect to the contribution expected from the “cocktail”  $\rho$  (bound to the  $\omega$  with  $\rho/\omega = 1$ , as measured in elementary collisions). The excess is centered around the nominal  $\rho$  pole position and is compatible with a strong broadening of the  $\rho$  spectral function and no mass shift. It monotonically increases and broadens with centrality. More details can be found in Ref. <sup>4,8</sup>

The data are corrected for the acceptance and for the centrality-dependent reconstruction efficiencies, estimated with an overlay Monte Carlo simulation (a Monte Carlo dimuon is reconstructed on top of a real event)<sup>10</sup>. Results on acceptance-corrected  $p_T$ -spectra for the mass window  $0.6 \leq M \leq 0.9$  GeV and non-peripheral collisions are shown in Fig. 1; equivalent data for other mass windows can be found Ref. <sup>10</sup>. The data of the three centrality windows agree within errors; this also holds for the other mass windows<sup>10</sup>. Fig. 2 (left) displays the centrality-integrated data vs. transverse mass  $m_T$  for four mass windows; the  $\phi$  is included for comparison. At very low  $m_T$ , a steepening is observed in all four mass windows, reminiscent of pion spectra and opposite to the expectation for radial flow at masses above the pion mass.

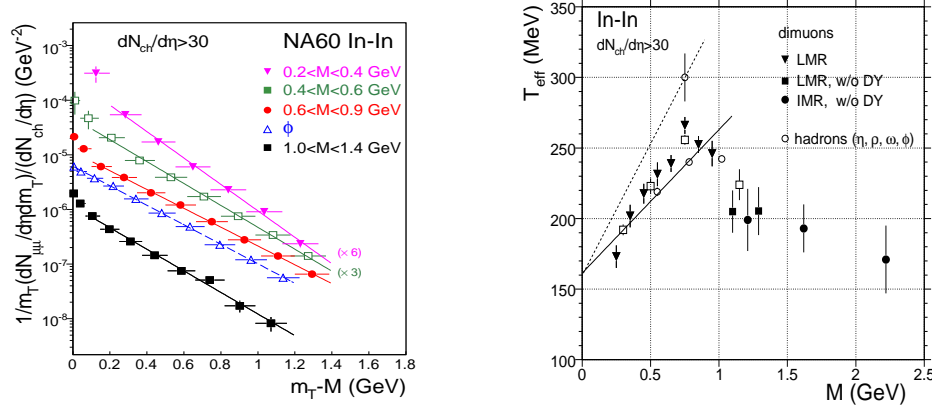


Figure 2: Left: Transverse mass spectra of the excess for four mass windows summed over centralities (excluding the peripheral bin), in comparison to the  $\phi$  (absolute normalization). Right: Inverse slope parameter  $T_{\text{eff}}$  vs. dimuon mass  $M$  for  $dN_{ch}/d\eta > 30$ . The open squares correspond to the fit lines in the left pane. Open charm is subtracted throughout. For explanation of the inserted symbols and the errors see text.

This steepening is not observed for the hadron spectra. The rise only disappears for very peripheral collisions ( $4 < dN_{ch}/d\eta < 10$ ). The lines in Fig. 2 (left) are fits with the exponential function  $1/m_T dN/dm_T \propto \exp(-m_T/T_{\text{eff}})$ . The fits are restricted to the range  $0.4 < p_T < 1.8$  GeV (roughly  $0.1 < (m_T - M) < 1.2$  GeV), to exclude the increased rise at low  $m_T$ . Fig. 2 (right) shows  $T_{\text{eff}}$  vs. pair mass, for the mass windows defined in the left pane (open squares) and for a finer mass binning (closed triangles). NA60 results from an independent analysis<sup>16</sup> of the intermediate mass region (“IMR”)  $1.16 < M < 2.56$  GeV, corrected for the contribution from Drell-Yan pairs, are shown for comparison. The hadron data as obtained from the subtraction procedure are also included; the value for the  $\eta$  has been obtained by tuning the GENESIS code<sup>15</sup> to the  $\eta$  Dalitz decay and then referring back to the required  $T_{\text{eff}}$  of the mother. The errors shown for the low-mass data (“LMR”) are purely statistical. The systematic error is smaller than the statistical one (see Ref.<sup>21</sup>).

The results shown in Fig. 2 (right) can be summarized and interpreted as follows. The slope parameter  $T_{\text{eff}}$  rises nearly linearly with mass up to about 270 MeV at the pole position of the  $\rho$ , followed by a sudden decline to values of 190-200 MeV for masses  $> 1$  GeV. The excess yield in the mass region  $0.2 < M < 0.9$  GeV is generally attributed to thermal radiation from the fireball, dominated by pion annihilation  $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$  via an in-medium modified  $\rho$ <sup>4</sup>. The NA60 data in this region are now nearly quantitatively described by theoretical models<sup>17,18,19</sup>. The linear rise of  $T_{\text{eff}}$  with  $M$  over the whole region up to the  $\rho$  peak is reminiscent of radial flow of a hadronic source. The hadron data show a similar linear rise, but their absolute values are surprisingly close to the excess values, contrary to the expectation for the temperature-flow folding. Hadrons should have larger flow, being emitted at freeze-out, while leptons are emitted throughout the whole lifetime of the fireball. To solve this seeming contradiction the vacuum  $\rho$  was studied. It can be isolated disentangling the peak from the broad continuum (Fig. 1, left)<sup>9,10,17,18,19</sup>. It is found  $T_{\text{eff}} = 300 \pm 17$  MeV for the peak and  $231 \pm 7$  for the underlying continuum in the window  $0.6 < M < 0.9$  MeV. The subtraction of a  $\rho$  modelled with the measured  $T_{\text{eff}}$  from the continuum data leads to differences of 4–20 MeV in  $T_{\text{eff}}$  depending on the closeness to the pole. The following interpretation emerges: the  $\rho$  is maximally coupled to pions and it is thus representative of the true freeze-out parameters of the fireball. The other hadrons freeze-out earlier, due to their smaller coupling to the pions. The large gap in  $T_{\text{eff}}$  between the vacuum  $\rho$  and the excess points is consistent with the expectations for the temperature-flow folding of the leptons. The linear rise of  $T_{\text{eff}}$  with  $M$  is consistent with the expectations for radial flow of a hadronic source ( $\pi\pi \rightarrow \rho$ ) decaying into lepton pairs. Theoretical understanding of these results is underway<sup>17,18,19</sup>, but does not yet describe the data in a satisfactory way. The large gap ( $> 50$  MeV) in  $T_{\text{eff}}$  between the vacuum  $\rho$  and the  $\omega$  only disappears for the lowest

peripheral “pp-like” selection  $4 < dN_{ch}/d\eta < 10$ , with  $T_{\text{eff}} = 198 \pm 6$  MeV for the  $\rho$  and  $201 \pm 4$  MeV for the  $\omega$ . This implies that the “hot  $\rho$ ” is intimately connected to pions, disappearing as the  $\pi\pi$  contribution to  $\rho$  production vanishes (with only the “cocktail”  $\rho$  left). The sudden decline of  $T_{\text{eff}}$  at masses  $> 1$  GeV is the other most remarkable feature of the present data, which may indicate a transition to a source of a different nature. Extrapolating the lower-mass trend to beyond 1 GeV, a jump by about 50 MeV down to a low-flow situation is extremely hard to reconcile with emission sources of dominantly hadronic origin. If the rise is due to flow, then the sudden loss of flow may be explained as a transition to a qualitatively different source, suggesting dominantly early (partonic) processes like  $q\bar{q} \rightarrow \mu^+\mu^-$  for which flow has not yet built up<sup>18</sup>. While still controversial<sup>17</sup>, this may well represent the first direct evidence for thermal radiation of partonic origin.

In conclusion, we have found strong evidence for radial flow in the region of thermal dilepton emission which has previously been associated with the  $\rho$  spectral function. The transition to a low-flow region above may signal a transition from a hadronic to a partonic source.

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